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A multimodal location and routing model for hazardous materials transportation based on multi-commodity flow model

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Abstract

The recent US Commodity Flow Survey data suggest that transporting hazardous materials (HAZMAT) often involves multiple modes, especially for long-distance transportation. However, not much research has been conducted on HAZMAT location and routing on a multimodal transportation network. Most existing HAZMAT location and routing studies focus exclusively on single mode (either highways or railways). Motivated by the less research on multimodal HAZMAT location and routing and the fact that there is an increasing demand for it, this research proposes a multimodal HAZMAT model that simultaneously optimizes the locations of transfer yards and transportation routes. A 0-1 decision variable is defined which could make the optimization results reflect HAZMAT flow routing which subjected to railway transport organization principles. The developed model is applied to the simplified local multimodal network in the Northeast China for example. Results show that ideal location and routing plan can be obtained.

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1. Introduction

Multimodal transportation has been used to move HAZMAT, the volume has been steadily increasing over the past decades. For example, the Bureau of Transportation Statistics estimated that over 111 million tons of hazmat was shipped across the US intermodal transportation system in 2007 (Bureau of Transportation Statistics and U.S.

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Census Bureau, 2010).

Existing HAZMAT transportation studies can generally be categorized into the following groups (Xie, et al., 2012): vehicle routing and scheduling, network design, risk modelling, facility location, integrated location and routing, and development of decision support systems. In this review, we choose to only focus on relevant HAZMAT transportation research, including vehicle routing, facility location and integrated location and routing studies.

A number of studies have addressed the HAZMAT vehicle routing problems. Sherali et al. (1997) proposed a routing model to minimize the risk of low probability-high consequence accidents, in which both the expected risk of accidents and the conditional expectation given that an accident has happened are considered. Nozick et al. (1997) proposed an integrated routing and scheduling model based on time-varying routing parameters. A study by Iakovou et al. (1999) developed a multi-commodity and multiple OD model for maritime HAZMAT routing. In a recent study by Wang et al. (2013) proposed an improved hybrid ant colony algorithm to optimize route for Hazardous Materials Logistics.

Some researchers pointed out the importance of multimodal HAZMAT location and routing. In a study conducted by Current and Ratick (1995), is to jointly model facility location and HAZMAT routing. The authors formulated the problem as a multi-objective mixed integer program. A similar model was developed by Cappanera et al. (2004) for the location and routing of obnoxious activities. Helander and Melachrinoudis (1997) developed a facility location and routing model to site a single facility. A path reliability measure was introduced to find the best facility location. A number of other studies also investigated the optimal locations and routing of hazardous materials (Giannikos, 1998; Zografos and Samara 1990; Revelle, et al., 1991; Stowers and Palekar, 1993). However, all these studies considered a single-mode (either railway or highway) network and the goal is to optimally site disposal/treatment facilities, which is different from the multi-modal location and routing model to be developed in this research.

Another important aspect closely related to the HAZMAT facility location and routing is risk modelling. The risk modelling is related to assessing the risk induced on the population by hazmat vehicles travelling on various segments. The risk analyses in these studies are including the fault tree method, a three-stage framework (List and Mirchandani, 1991.). Since our focus is not risk modelling, a detailed review of these methods is beyond the scope of this research. In this study, a simple while commonly used risk calculation method is adopted.

In a recently study conducted by Xie et al. (2012), it is the first attempt to simultaneously optimize the locations of multimodal transfer yards and transportation routes based on extensive literature review. Inspired by it, our paper brings in some new ideas and adjusts some inappropriate details. A 0-1 decision variable is defined which could make the optimization results reflect HAZMAT flow routing which subjected to railway transport organization principles.

The remainder of this paper is organized as follows. In Section 2, we define the problem of interest and state the assumptions. Section 3 presents the bi-objective framework. Section 4 makes use of the intermodal modal to discuss a simplified local multimodal network in the Northeast China, which are solved and analyzed to provide detailed model outputs to better illustrate how the developed model works. Conclusion is outlined in Section 5.

2. 2. Problem statement

In this section, we provide a formal statement of the problem, and state the modelling assumptions.

Modelling multimodal HAZMAT location and routing is significantly different from its single-mode counterpart. It requires the transfer of HAZMAT containers or tanks between different modes, which typically needs special equipment and trained operators with particular expertise. Due to budget and cost considerations, it would be unwise for the carriers/shippers to invest in all candidate intermodal facilities (transfer yards) and to make them available for HAZMAT transfer. In addition, the locations of these transfer yards can have a significant impact on the optimal routing decisions and consequently on the total transportation risk and cost. It is important to consider the locations of HAZMAT transfer facilities and the routing plans simultaneously.

Our problem is to determine the best subset of location from all candidate transfer yards and also to find the best transportation routing plan for hazardous in a multimodal network based on the selected transfer yards. The

objective is to minimize the total cost of transportation as well as the total public risk associated with hazmat. The problem under investigation in this study is inspired by research conducted by Xie et al. (2012) and inherits the idea. It is fundamentally different from all previous research. First, we choose to optimize the HAZMAT location and routing plans that involve multiple modes. This is becoming increasingly important for HAZMAT transportation. However, this particular area has not been adequately studied yet and most previous studies on HAZMAT location and routing dealt with single mode. Second, all existing integrated location and routing HAZMAT models are designed specifically for sitting either disposal or treatment facilities, while this research aims at optimally sitting transfer yards.

We now turn to our modelling assumption: we define a 0-1 decision variable which could make the optimization results reflect HAZMAT flow routing which subjected to transport organization principles that each HAZMAT flow moving on one route only. The assumption is agreed with the reality situation of China.

3.3. Bi-objective framework

A multimodal network consisting of railways and highways is considered in this research. This network is described by a directed graph $G = (N, E)$, where $N = \{N_H, N_R, N_{HR}\}$ is the node set and $E = \{E_H, E_R\}$ is the edge set. The node set consists of three subsets: N_H , N_R and N_{HR} . N_H represents nodes where highways connect or end; N_R represents nodes where railways connect or end; and N_{HR} is for nodes where railways connect to highways and HAZMAT shipments can be transferred between the two modes. There are no transfer activities at highway (N_H) or railway (N_R) nodes. At the planning stage, all nodes in N_{HR} can be considered as the candidate locations for HAZMAT transfer yards. Each candidate transfer yard $i \in N_{HR}$ has a per-shipment risk (r_i) associated with it due to the potential HAZMAT spills caused by the transfer operations. Each candidate transfer yard also has a total cost (f_i) consisting of an annualized capital cost and an operating cost. These risk and cost factors will affect whether a candidate site should be selected or not. Each edge $(i, j) \in E$, has a per-shipment risk (r_{ij}) and per-shipment cost (l_{ij}) associated with it. For transfer yards, their total costs (f_i) in many cases are affected not only by the number of HAZMAT shipments, but also by other important factors such as the size/capacity of the yards. These costs in general are independent of the demand (number of shipments per year). In addition, the total cost (f_i) in this study also includes the annualized capital cost, which is independent of the number of HAZMAT shipments as well. Since the proposed model is for planning purpose, deterministic and time-independent link travel risk and cost are considered. In addition, we consider multiple Original-Destination (OD) pairs and a single type of HAZMAT.

To optimize the HAZMAT location and routing plans, the planner needs to make the following decisions: (i) determine the best location from all candidate transfer yards and, (ii) to find the best transportation routing plan for hazardous in a multimodal network based on the selected transfer yards. These decisions can be expressed by variables:

$$X_{ij}^c = \begin{cases} 1 & \text{if the HAZMAT flow for the } c\text{th OD uses link } (i, j) \\ 0 & \text{otherwise} \end{cases}, \forall (i, j) \in E$$

$$Z_i = \begin{cases} 1 & \text{if transfer yard } i \text{ is selected} \\ 0 & \text{otherwise} \end{cases}, \forall i \in N_{HR}$$

$$T_i^c = \begin{cases} 1 & \text{if the HAZMAT flow for the } c\text{th OD transfers at yard } i \\ 0 & \text{otherwise} \end{cases}, \forall i \in N_{HR}$$

The HAZMAT location and routing problems reviewed are often formulated as multi-objective optimizations. The aforementioned problem is also initially formulated as a multi-objective integer program in Eqs. (1) – (9). There are two major components in the objective function (Eq. (1)), which account for the total risk and total cost.

$$\begin{aligned} \text{Cost: } \min &= \alpha \sum_{c \in C} \sum_{(i,j) \in E} n^c X_{ij}^c \cdot l_{ij} + \alpha \sum_{i \in N_{HR}} f_i Z_i \\ \text{Risk: } \min &= \beta \sum_{c \in C} \sum_{(i,j) \in E} n^c X_{ij}^c \cdot r_{ij} + \beta \sum_{i \in N_{HR}} \sum_{c \in C} n^c T_i^c \cdot r_i \end{aligned} \quad (1)$$

s.t.

$$\sum_{(i,k) \in E_H \cup E_R} X_{ik}^c - \sum_{(k,i) \in E_H \cup E_R} X_{ki}^c = \begin{cases} +1 & i = \text{orig}(c) \\ 0 & \text{otherwise} \\ -1 & i = \text{dest}(c) \end{cases}, \forall i \in E_H \cup E_R, c \in C \quad (2)$$

$$\sum_{(i,k) \in E_H} X_{ik}^c + Z_i \sum_{(i,m) \in E_R} X_{im}^c - \sum_{(k,i) \in E_H} X_{ki}^c - Z_i \sum_{(m,i) \in E_R} X_{mi}^c = 0, \forall i \in N_{HR}, c \in C \quad (3)$$

$$T_i^c = \left| \sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c \right|, \forall i \in E_{HR}, c \in C \quad (4)$$

$$\sum_{c \in C} n^c T_i^c \leq CAP_i \cdot Z_i, \forall i \in N_{HR} \quad (5)$$

$$\sum_{c \in C} n^c X_{ij}^c \leq CAP_{ij}, \forall (i,j) \in E \quad (6)$$

$$X_{ij}^c \in \{0,1\}, \forall (i,j) \in E, c \in C \quad (7)$$

$$T_i^c \in \{0,1\}, \forall i \in N_{HR}, c \in C \quad (8)$$

$$Z_i \in \{0,1\}, \forall i \in N_{HR} \quad (9)$$

where C is the set of OD pairs; CAP_i is the capacity of candidate transfer yard i ; CAP_{ij} is the capacity of link (i,j) . $\text{orig}(c)$ is the origin node of the c th OD pair; $\text{dest}(c)$ is the destination node of the c th OD pair. α and β are weights for costs and risks, respectively.

The first set of constraints (Eq. (2)) is to ensure flow conservation for highway and railway nodes; Eq. (3) is the flow conservation constraints for candidate transfer yards; Eq. (4) defines a new variable T_i^c representing the shipments for the c th OD pair that are transferred at the i th candidate yard. Each candidate transfer yard and transportation link can only handle a limited number of HAZMAT shipments and the capacities are reflected in Eq. (5) and Eq. (6).

The model formulation introduced in the previous section is easy to understand. However, it is nonlinear and also contains an absolute term, which makes it very difficult to solve. In this section, this model is reformulated. Several new constraints are introduced to replace the nonlinear and the absolute terms. Although the new formulation is less straightforward, it is in a mixed integer linear form and is relatively easy to solve. M denotes a very large value. All other symbols used in Eqs. (10)-(13) have been introduced previously and will not be duplicated here.

Eqs. (10)-(12) are equivalent to Eq. (3). They are to ensure that if candidate yard i is not selected ($Z_i = 0$), the in and out highway and railway HAZMAT flows at node i must be equal. Also, if candidate yard i is selected, the in and out HAZMAT flows of all modes at node i are equal.

$$-M \cdot Z_i \leq \sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c \leq M \cdot Z_i, \forall i \in N_{HR}, c \in C \quad (10)$$

$$-M \cdot Z_i \leq \sum_{(i,k) \in E_R} X_{ik}^c - \sum_{(k,i) \in E_R} X_{ki}^c \leq M \cdot Z_i, \forall i \in N_{HR}, c \in C \quad (11)$$

$$\begin{aligned} & \sum_{(m,i) \in E_R} X_{mi}^c - \sum_{(i,m) \in E_R} X_{im}^c - M(1 - Z_i) \leq \sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c \\ & \leq \sum_{(m,i) \in E_R} X_{mi}^c - \sum_{(i,m) \in E_R} X_{im}^c + M(1 - Z_i), \forall i \in N_{HR}, c \in C \end{aligned} \quad (12)$$

Eq. (13) corresponds to Eq. (4) as shown above

$$-T_i^c \leq \sum_{(i,k) \in E_H} X_{ik}^c - \sum_{(k,i) \in E_H} X_{ki}^c \leq T_i^c, \forall i \in E_{HR}, c \in C \quad (13)$$

The new constraints (Eqs. (10)-(13)) are essentially equivalent to the nonlinear and discontinuous constraints in Eqs. (3)-(4). By getting rid of the nonlinear and discontinuous terms, the original model formulation becomes a 0-1 integer linear program, which can be solved directly by some off-the-shelf optimization tools such as Lingo.

4. 4. Computational results

The case study is a simplified local multimodal network in the Northeast China consisting of major railways and intercity highways among 14 cities (Fig.1). It is conducted to demonstrate how the proposed model can be used for multimodal HAZMAT location and routing modelling.

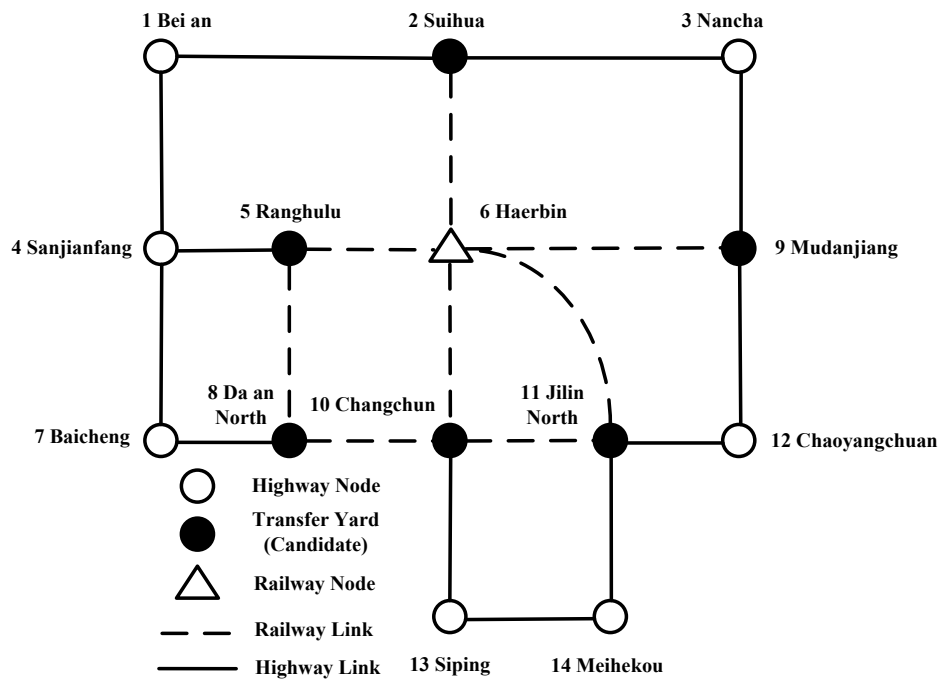


Fig.1. Network for case study

The transportation costs for railways and highways are set to be 0.24 and 1.07 per kilometer per shipment, respectively. The unitary accident frequency for railways and highways are assumed to be 0.019 and 0.062 people per shipment, respectively.

Nodes 2, 5, 8, 9, 10, and 11 are candidate transfer yards. Their annualized construction and operating costs, capacities, and per-shipment risks are listed in Table. 1. Due to the lack of real-world data, the numbers in Table 1 and the demand data used are all hypothetical values.

Table 1. Candidate transfer yard information

| Yard ID | f_i , annual cost (1000/year) | CAP_i , yard capacity (shipments/year) | r_i , risk per shipment (number of people/shipment) |
|---------|------------------------------------|---|--|
| 2 | 845000 | 200 | 0.59 |
| 5 | 753000 | 200 | 0.52 |
| 8 | 722000 | 200 | 0.36 |
| 9 | 998000 | 200 | 0.85 |
| 10 | 657000 | 200 | 0.70 |
| 11 | 846000 | 200 | 0.17 |

The realistic-size network consists of major railways and intercity highways. The distance and capacity of all links are list in Table.2. The demand is list in Table.3.

Table 2. Link information

| # | (i, j) | Distance (km) | CAP_i (10^4 shipments) |
|----|----------|---------------|--------------------------------|
| 1 | 1-2 | 208 | 100 |
| 2 | 1-4 | 261 | 160 |
| 3 | 2-3 | 229 | 100 |
| 4 | 2-6 | 125 | 100 |
| 5 | 3-9 | 485 | 100 |
| 6 | 4-5 | 104 | 100 |
| 7 | 4-7 | 188 | 100 |
| 8 | 5-6 | 170 | 160 |
| 9 | 5-8 | 145 | 100 |
| 10 | 6-9 | 370 | 100 |
| 11 | 6-10 | 249 | 160 |
| 12 | 6-11 | 279 | 160 |
| 13 | 9-12 | 901 | 100 |
| 14 | 10-11 | 128 | 160 |
| 15 | 10-13 | 116 | 160 |
| 16 | 11-12 | 338 | 160 |
| 17 | 11-14 | 218 | 160 |
| 18 | 13-14 | 155 | 100 |
| 19 | 7-8 | 115 | 100 |
| 20 | 8-10 | 218 | 100 |

Table 3. Demand

| # | Orgi. | Dest. | OD (10^4 shipments) |
|----|-------|-------|------------------------|
| 1 | 2 | 13 | 82 |
| 2 | 1 | 11 | 26 |
| 3 | 1 | 12 | 28 |
| 4 | 3 | 4 | 28 |
| 5 | 4 | 9 | 27 |
| 6 | 4 | 11 | 10 |
| 7 | 5 | 11 | 38 |
| 8 | 4 | 10 | 20 |
| 9 | 12 | 7 | 34 |
| 10 | 12 | 5 | 24 |
| 11 | 14 | 6 | 38 |
| 12 | 8 | 14 | 24 |

The base case with weight ($\alpha = 0.5$ and $\beta = 0.5$) is considered as shown in Table 4. The proposed model is coded in Lingo and solved to optimality. As the result shows that each OD pair has only one optimal route.

Table 4. Routing plan

| # | Selected yards | Optimal routes |
|----|----------------|----------------|
| 1 | | 2-6-10-13 |
| 2 | | 1-4-5-6-11 |
| 3 | | 1-4-5-6-11-12 |
| 4 | | 3-2-1-4 |
| 5 | | 4-5-6-9 |
| 6 | 5,8 | 4-5-6-11 |
| 7 | 10,11 | 5-6-11 |
| 8 | | 4-7-8-10 |
| 9 | | 12-11-10-8-7 |
| 10 | | 12-11-6-5 |
| 11 | | 14-11-6 |
| 12 | | 8-10-13-14 |

In addition to provide detailed model outputs, we report on the parametric analysis performed by varying the weights associated with the two objectives. The values of the risk and cost components in the objective function for different scenarios are presented in both Table 5 and Fig. 2.

Table 5. Scenarios produced by different weights

| Legends | Total cost(1000/year) | Total risk (number of people/year) |
|-----------------------|-----------------------|---------------------------------------|
| Min cost | 4,343,410 | 3,195,700 |
| A=[cost=0.9,risk=0.1] | 4,354,261 | 2,512,947 |
| B=[cost=0.8,risk=0.2] | 4,354,680 | 2,319,069 |
| C=[cost=0.7,risk=0.3] | 4,367,414 | 2,211,661 |
| D=[cost=0.6,risk=0.4] | 4,401,529 | 2,043,656 |
| Base case | 4,428,275 | 1,927,390 |
| E=[cost=0.4,risk=0.6] | 4,491,891 | 1,748,856 |
| F=[cost=0.3,risk=0.7] | 4,517,351 | 1,685,039 |
| G=[cost=0.2,risk=0.8] | 4,561,726 | 1,637,293 |
| H=[cost=0.1,risk=0.9] | 4,619,097 | 1,603,202 |
| Min risk | 4,709,796 | 1,596,142 |

Note that both of these weights are 0.5 in the Base Case. Each row in Table 5 (or each point in Fig.2) represents a solution, with the min cost and the min risk constituting the two extremes. The min cost solution is 1.9% less expensive than the Base-Case solution, but 66% more risky. On the other hand the min risk solution is 6.4% more expensive.

From Table 5 (and Fig. 2) one sees that the min cost solution entails a cost of around 4343 million and exposes 3.2 million people, whereas the min risk solution will cost 4709 million and expose 1.6 million people. By spending an extra 366 million, it is possible to halve the population exposure risk. This may be a worthwhile trade-off for the regulators to pursue.

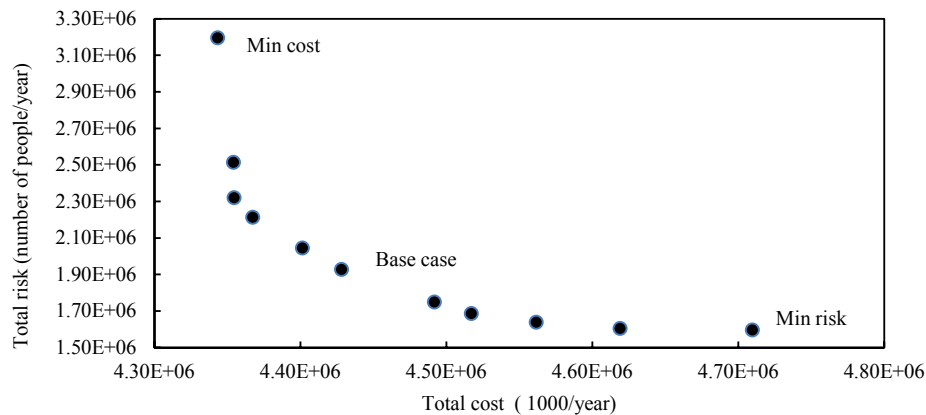


Fig.2. Weight based solutions

Perhaps another more important observation is the significant increase in population exposure risk when the weight attached to the risk coefficient is decreased from 10% to 0% (i.e., from A to Min Cost). This weight allocation results in a saving of around 10 million but increases exposure risk by 0.6 million people.

5. 5. Conclusion remarks

Multimodal transportation is playing an increasingly important role in HAZMAT transportation practices, which requires more research on multimodal HAZMAT location and routing modeling. Despite the growing needs, little attention has been paid to this relatively new area.

This research is among the few studies focusing on the location and routing modeling of multimodal HAZMAT transportation. The achievement by Y.C. Xie et al. inspires our research a lot. It also is the first attempt to address the optimization of transfer yard locations and routing plans simultaneously.

In this paper, we propose a multi-objective and multimodal model that can simultaneously optimize transfer yard locations and HAZMAT transportation routes. The optimization results reflect HAZMAT flow routing intuitively via introducing a 0-1 decision variable. The proposed model is tested on the simplified local multimodal network in the Northeast China consisting of highways and railways.

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